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Climate Change Science: Key Points

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Summary

Though climate change science often is portrayed as controversial, broad scientific agreement exists on many points:

- The Earth's climate is warming and changing.
- Human-related emissions of greenhouse gases (GHG) and other pollutants have contributed to warming observed since the 1970s and, if continued, would tend to drive further warming, sea level rise, and other climate shifts.
- Volcanoes, the Earth's relationship to the Sun, solar cycles, and land cover change may be more influential on climate shifts than rising GHG concentrations on other time and geographic scales. Human-induced changes are super-imposed on and interact with natural climate variability.
- The largest uncertainties in climate projections surround feedbacks in the Earth system that augment or dampen the initial influence, or affect the pattern of changes. Feedback mechanisms are apparent in clouds, vegetation, oceans, and potential emissions from soils.
- There is a wide range of projections of future, human-induced climate change, all pointing toward warming and associated sea level rise, with wider uncertainties regarding the nature of precipitation, storms, and other important aspects of climate.
- Human societies and ecosystems are sensitive to climate. Some past climate changes benefited civilizations; others contributed to the demise of some societies. Small future changes may bring benefits for some and adverse effects to others. Large climate changes would be increasingly adverse for a widening scope of populations and ecosystems.

As is common and constructive in science, scientists debate finer points. For example, a large majority but not all scientists find compelling evidence that rising GHG have contributed the most influence on global warming since the 1970s, with solar radiation a smaller influence on that time scale. Most climate modelers project important impacts of unabated GHG emissions, with low likelihoods of catastrophic impacts over this century. Human influences on climate change would continue for centuries after atmospheric concentrations of GHG are stabilized, as the accumulated gases continue to exert effects and as the Earth's systems seek to equilibrate.

The U.S. government and others have invested billions of dollars in research to improve understanding of the Earth's climate system, resulting in major improvements in understanding while major uncertainties remain. However, it is fundamental to the scientific method that science does not provide absolute proofs; all scientific theories are to some degree provisional and may be rejected or modified based on new evidence. Private and public decisions to act or not to act, to reduce the human contribution to climate change or to prepare for future changes, will be made in the context of accumulating evidence (or lack of evidence), accumulating GHG concentrations, ongoing debate about risks, and other considerations (e.g., economics and distributional effects).

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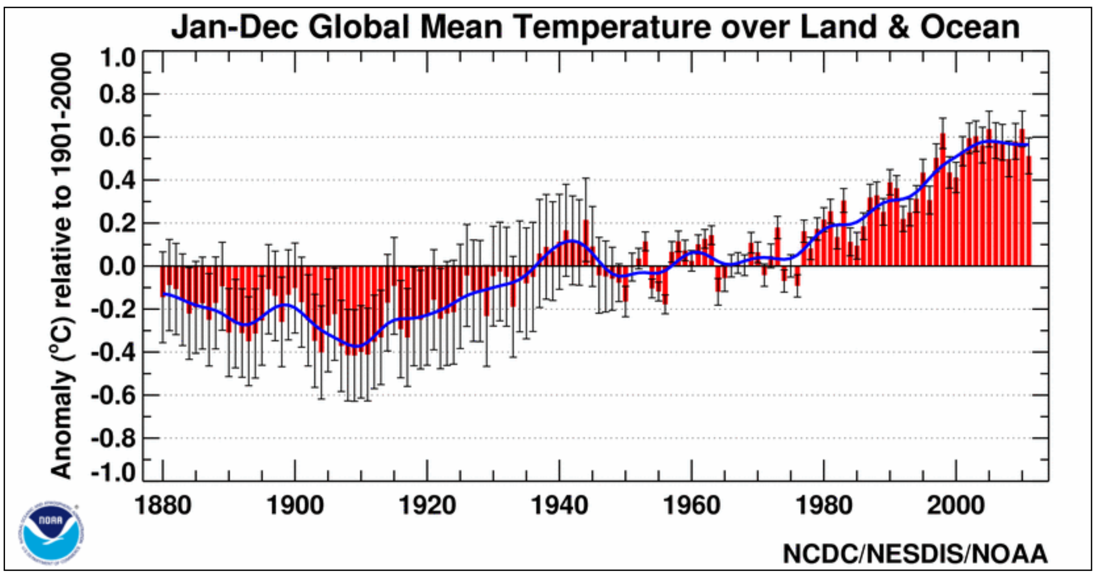
Broad Scientific Agreement on Many Aspects of Climate Change[1]

Despite portrayals in popular media about controversies in climate change science, almost all climate scientists agree on certain important points:

- The Earth's climate has warmed significantly and changed in other ways over the past century (**Figure 1**). The warming has been widespread but not uniform globally, with most warming over continents at high latitudes, and slight cooling in a few regions, including the southeastern United States, the Amazon, and the North Atlantic south of Greenland.[2]

Figure 1. Long-Term Temperature Observations

Compared to the 20th Century Global Mean Temperature



Source: National Climate Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Figure extracted March 28, 2013. Very similar findings are reported by several other, independent research groups. See, for example, Rohde, Robert, Richard Muller, Robert Jacobsen, Elizabeth Muller, Saul Perlmutter, Arthur Rosenfeld, Jonathan Wurtele, Donald Groom, and Charlotte Wickham. "A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011." *Geoinformatics & Geostatistics: An Overview* 1, no. 1 (December 7, 2012).

Notes: Red bars represent "anomalies," or differences in mean temperature for the year compared with the 20th century average. Anomalies are a better estimate than the absolute value, as they can capture the change over time more reliably while absolute values are vulnerable to gaps in geographic coverage. The blue line shows the running average, applying a "21-point binomial filter" to the time series plotted as red bars. The "whisker" (thin black vertical) lines represent confidence or possible error levels. Confidence has improved over the past century.

[1] This CRS report will be reviewed and, as appropriate, revised considering evidence provided from emerging scientific research. Of, note, the Intergovernmental Panel on Climate Change (IPCC) will release its fifth assessment report later in 2013.

[2] For more information, see maps available at the National Climate Data Center, http://www.ncdc.noaa.gov/oa/climate/globalwarming.html and http://www.ncdc.noaa.gov/oa/climate/research/trends.html#global.

- The climate has varied naturally through geologic history. Past climate changes sometimes proceeded abruptly when they passed certain "tipping points." The National Academy of Sciences concluded that the past few decades were very likely the warmest in the past 400 years, and "that temperatures at many, but not all, individual locations were higher during the past 25 years than during any period of comparable length since A.D. 900."[3] Although conclusions cannot yet be precise, research suggests that global average temperatures today are among the highest since human civilizations began to flourish roughly 4,000 to 8,000 years ago.[4]
- "Greenhouse gases" (GHG) include, among others, carbon dioxide (CO_2), water vapor, methane (CH_4), and nitrous oxide (N_2O), as well as some aerosols. They absorb energy into the atmosphere rather than letting it escape to space. The presence of GHG in the atmosphere warms the Earth to its current temperature.
- Human activities, especially fossil fuel burning, deforestation, agriculture, and some types of industry, have increased GHG concentrations in the atmosphere. CO_2, the main GHG emitted by human activities, has risen almost 40% over the past 150 years. About one-third of human-related CO_2 has been absorbed by oceans, increasing surface water acidity by 30%.[5]
- The enhanced levels of GHG in the atmosphere contributed to the observed global average warming in recent decades. Over other time and geographic scales, such factors as the Earth's orbit, solar variability, volcanoes, and land cover change have been stronger influences than human-related GHG.
- There is a wide range of projections of future human-induced climate change, with all pointing toward warming. Human-induced change will be superimposed on, and interact with, natural climate variability.
- Human societies and ecosystems are sensitive to climate. Some climate changes benefited civilizations; others contributed to some societies' demises.
- The range of possible impacts on humans and ecosystems is also very wide. In the near term, climate change (including the fertilization of vegetation by CO_2) may bring benefits for some, while adversely affecting others. Researchers expect the balance of projected climate change impacts to be increasingly adverse for a widening scope of populations and ecosystems.

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[3] Board on Atmospheric Sciences and Climate. *Surface Temperature Reconstructions for the Last 2,000 Years*. National Research Council, 2006. http://books.nap.edu/openbook.php?record_id=11676&page=1.

[4] Marcott, Shaun A., Jeremy D. Shakun, Peter U. Clark, and Alan C. Mix. "A Reconstruction of Regional and Global Temperature for the Past 11,300 Years." *Science* 339, no. 6124 (March 8, 2013): 1198–1201. doi:10.1126/science.1228026; Kellerhals, T., S. Brütsch, M. Sigl, S. Knüsel, H. W. Gäggeler, and M. Schwikowski. "Ammonium Concentration in Ice Cores: A New Proxy for Regional Temperature Reconstruction?" *Journal of Geophysical Research: Atmospheres* 115, no. D16 (2010): n/a–n/a. doi:10.1029/2009JD012603; Thibodeau, Benoît, Anne de Vernal, Claude Hillaire-Marcel, and Alfonso Mucci. "Twentieth Century Warming in Deep Waters of the Gulf of St. Lawrence: A Unique Feature of the Last Millennium." *Geophysical Research Letters* 37, no. 17 (2010): n/a–n/a. doi:10.1029/2010GL044771. See also the references at http://www.globalwarmingart.com/wiki/File:Holocene_Temperature_Variations_Rev_png, which depict a collection of major temperature reconstructions of the Holocene, as well as the broad range of uncertainty of available estimates and the average of those estimates.

[5] National Research Council. *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Washington DC, 2013; Feely, Richard A. 2010. A Rational Discussion of Climate Change: The Science, the Evidence, the Response. Testimony before the House Committee on Science and Technology, Subcommittee on Energy and Commerce. Washington DC. (p.130). See also CRS Report R43185, *Ocean Acidification*, by Harold F. Upton and Peter Folger.

As is common and constructive in science, scientists debate finer points. Some disagree with the broader consensus that GHG have been *the major* influence on global warming over the past few decades. Some suggest that, if GHG emissions continue unabated, the resulting climate change would be small and possibly beneficial overall. Most climate modelers project changes that are significant to large, with small likelihoods of changes that could be catastrophic for some human societies and ecosystems in coming decades.

Dealing with Uncertainties

Even the best science cannot provide absolute proof; it is fundamental to the scientific method that all theories are to some degree provisional and may be rejected or modified based on new evidence. Private and public decisions to act or not to act, to reduce the human contribution to climate change or to prepare for future changes, will be made in the context of accumulating evidence (or lack of evidence), accumulating GHG concentrations, ongoing debate about risks, and other considerations (e.g., economics and distributional effects).

Sound Science Does Not Offer Proof

As scientists may point out, "there is no such thing as a scientific proof. Proofs exist only in mathematics and logic, not in science.... The primary criterion and standard of evaluation of scientific theory is evidence, not proof.... The currently accepted theory of a phenomenon is simply the best explanation for it *among all available alternatives*."[6] Normal scientific methods aim at disproving a hypothesis; if evidence cannot disprove a hypothesis, it generally buttresses confidence in the hypothesis.

That said, billions of dollars have been invested in research on a wide range of climate change topics, including the possibility of attribution to alternative causes than greenhouse gases. To date, scientists have found little support for the hypothesis that GHG are not responsible for observed warming, nor have they found much evidence that other factors (including solar changes) can explain more than a small portion of global average temperature increases since the 1970s. For example, measurements of solar irradiance suggest that the solar influence on global temperatures has been decreasing overall since the 1930s, with the up-and-down pattern of the 11-year solar cycle evident in observations. A large body of research is consistent with attributing the majority of global temperature increase since the 1970s to the increase in GHG concentrations. It is this balance of evidence that leads most scientists to consider human-related GHG emissions an important global risk.

Issues for Congress

It appears unlikely that science will provide decision-makers with significantly more scientific certainty for many years regarding the precise patterns and risks of climate change. Nonetheless, both private and public decision-makers face climate-related choices.

Broadly, response options to significant climate change include (1) defer the choices; (2) find out more; (3) inform affected populations; (4) prepare; (5) try to contain it; and (6) choose to experience the consequences. In many cases, many decision-makers are likely to face situations that require a response, such as resolving discrepancies between designated and actual flood plains or attempting to improve agricultural productivity in light of contemporary climate patterns.

[6] See, for example, the discussion in Kanazawa, Satoshi. "Common misconceptions about science I: "Scientific proof"." *Psychology Today*, November 16, 2008. http://www.psychologytoday.com/blog/the-scientific-fundamentalist/200811/common-misconceptions-about-science-i-scientific-proof.

Based on what is and what is not well known concerning climate change, as well as other considerations, Members of Congress may address climate-related decisions that affect

- authorizations and appropriations for federal programs, including research and technology development;
- tax and financial incentives for private decision-makers;
- regulatory authorities; or
- information or assistance to affected entities to help them adapt or rebuild after damages.

A variety of other CRS reports provide background and analysis on such options and are listed at the end of this report.[7]

Causes of Observed Climate Change: Forcings, Feedbacks, and Internal Variability

Three concepts may be useful for understanding the mechanisms and debate over the contributions to observed climate change: *forcings, feedbacks*, and *internal variability*.

Forcings

There is broad agreement among scientists that certain factors—including the composition of the atmosphere and solar variability—directly change the balance between incoming and outgoing radiation in the Earth's system and consequently *force* climate change. *Forcings* include the following:

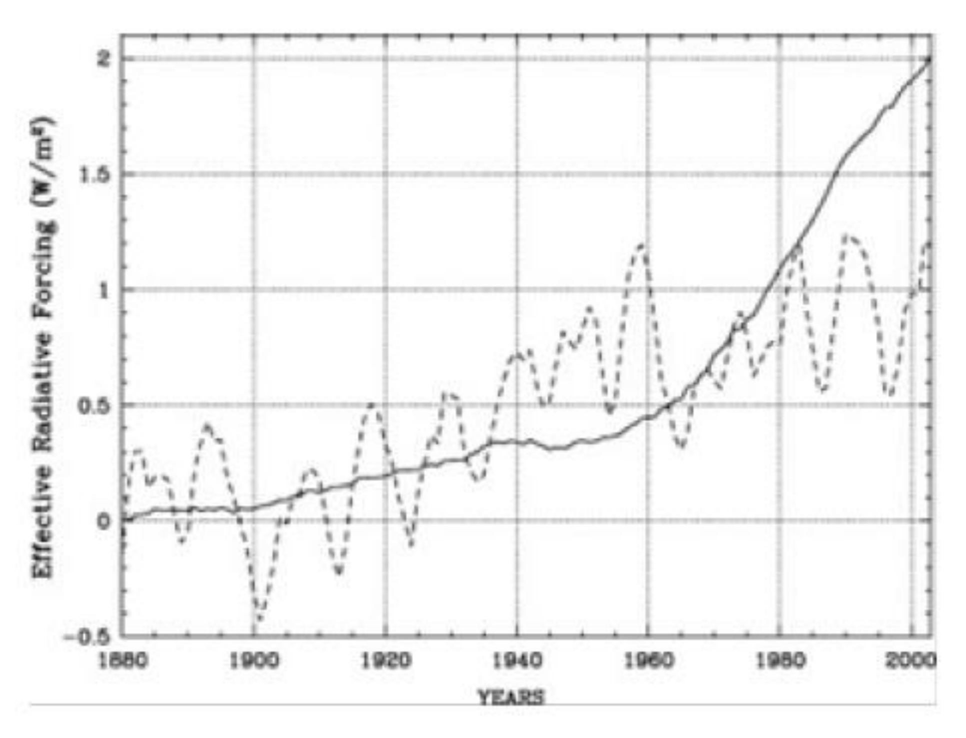
- **Atmospheric concentrations of greenhouse gas (GHG) and other trace gas and aerosol.** These include water vapor,[8] carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexaflouride (SF_6), chlorofluorocarbons (CFC), hydrofluorocarbons (HFC), perfluorocarbons (PFC), ozone, sulfur aerosols, black and organic carbon aerosols, and others. Human activities, especially fossil fuel burning, deforestation, agriculture, and some types of industry, have increased GHG concentrations in the atmosphere. CO_2 has risen almost 40% over the past 150 years.[9]
- Amount and patterns of **solar radiation** reaching the Earth due to the Earth's orbit around the Sun, and the tilt and wobble of the Earth's axis, as well as solar variability (**Figure 2**).
- **Reflectivity of the Earth's surface** due to changes in land use (e.g., urban surfaces, forest cover), changes in ice and snow cover; and vegetation cover.

[7] Many CRS reports related to climate change may be found at Issues Before Congress: Climate Change Science, Technology, and Policy, at http://www.crs.gov/pages/subissue.aspx?cliid=3878&parentid=2522&preview=False.

[8] Water vapor is the most important GHG in the atmosphere but is understood not to be directly influenced by humans; it would be, however, involved in feedback mechanisms, discussed later.

[9] About one-third of human-related CO_2 has been absorbed by oceans, increasing surface water acidity by 30%. See National Research Council. *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Washington, DC, 2013; Feely, Richard A. 2010. A Rational Discussion of Climate Change: The Science, the Evidence, the Response. Testimony before the House Committee on Science and Technology, Subcommittee on Energy and Commerce. Washington, DC. (p.130).

Figure 2. One Estimate of Human-Related versus Solar Contributions to Global Temperature Change Over the 20th Century



Source: Ziskin, Shlomi, and Nir J. Shaviv. "Quantifying the Role of Solar Radiative Forcing over the 20th Century." *Advances in Space Research* 50, no. 6 (September 15, 2012): 762–776. doi:10.1016/j.asr.2011.10.009.

Notes: According to the authors, "the optimal anthropogenic contribution (solid line) and the optimal solar contribution (dashed line) over the 20th century. The anthropogenic contribution is primarily composed of GHGs and aerosols. The solar contribution includes changes in the total solar irradiance and the indirect solar effect (ISE)." This is one of many studies, using a variety of methods, investigating the relative contributions of different climate forcings that conclude that the GHG concentrations have outweighed all other influences on global mean air surface temperature from the late 1970s to the present. For a broader, more thorough review of scientific understanding of the solar influence, see Gray, L. J., J. Beer, M. Geller, J. D. Haigh, M. Lockwood, K. Matthes, U. Cubasch, et al. "Solar Influences on Climate." *Reviews of Geophysics* 48, no. 4 (October 30, 2010). doi:10.1029/2009RG000282.

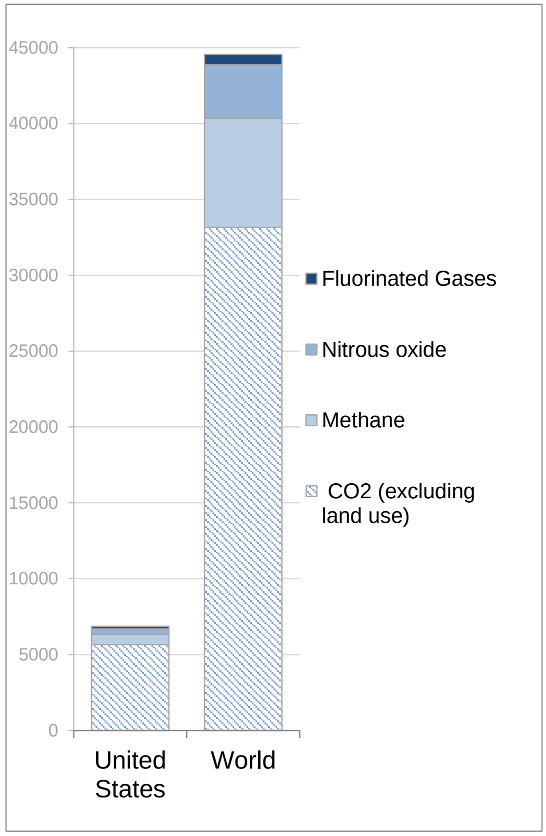
Human-Related Greenhouse Gas Emissions

A majority of human-related GHG emissions are carbon dioxide, released primarily from energy production and use, deforestation and forest degradation, and cement manufacture. World-wide in 2010, carbon dioxide emissions were 74% of human-related GHG emissions. In the United States, carbon dioxide was 83% of human-related GHG emissions (**Figure 3**). Methane and nitrous oxide emissions are greater shares (16% and 8%, respectively) globally than in the United States (10% and 5%, respectively). Agriculture is a main source of these emissions and is a bigger share of the economies of many low-income countries compared with the United States. Also, many sources in the United States have acted to reduce their GHG emissions (such as in reducing leaks of methane), compared with sources in some low-income countries.

A large majority (73%) of global GHG are emitted by the 10 top emitting countries **Figure 4**). China became the leading GHG emitter in 2007 when it surpassed the United States. While China's emissions have been on the rise, the United States has emitted more cumulatively than any other country over the past 100 years.

Figure 3. Shares of Human-Related GHG Emissions by Gas in 2010

million metric tons of CO_2-equivalent



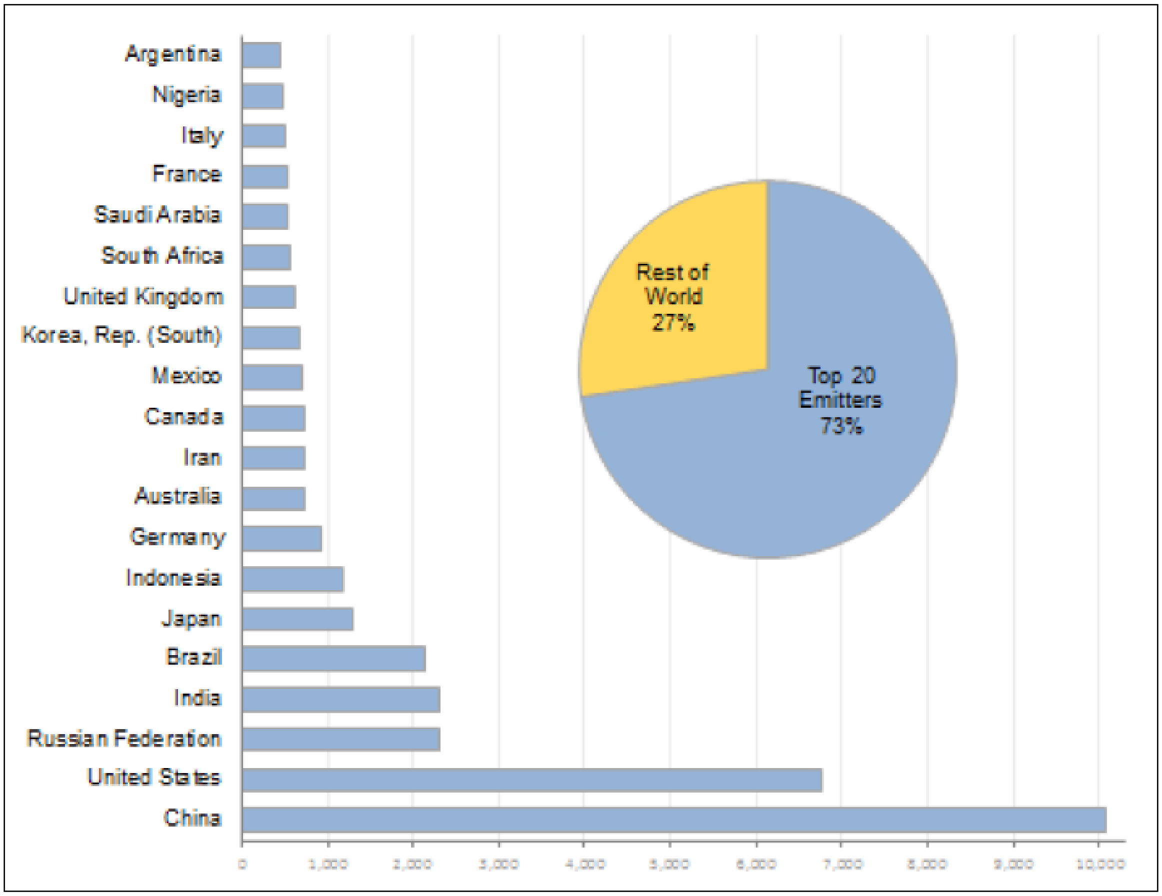
Source: CRS figure using estimates from World Resources Institute, CAIT version 2.0, extracted September 12, 2013.

Notes: These estimates cover the six GHG covered by the Kyoto Protocol (CO_2, CH_4, N_2O, SF_6, HFC, and PFC), expressed in their equivalencies to the effect of CO_2 on "radiative forcing" of the atmosphere over a 100-year period.

The World column includes U.S. emissions.

Figure 4. Estimated Top 20 Emitting Nations of Greenhouse Gases in 2010

million metric tons of carbon-dioxide equivalent, includes all net land use fluxes



Source: CRS graphic with emission estimates from World Resources Institute, CAIT Version 2.0, extracted September 12, 2013.

Notes: These estimates cover the six GHG covered by the Kyoto Protocol (CO_2, CH_4, N_2O, SF_6, HFC, and PFC), expressed in their equivalencies to the effect of CO_2 on "radiative forcing" of the atmosphere over a 100-year period.

Feedbacks

Once a change in the Earth's climate system is underway, responses *within* the system will amplify or dampen the initiated change. Virtually all climate scientists conclude that all the feedbacks *in net* are likely to be positive (i.e., increasing climate change in the same direction caused by warming),[10] especially if temperature increases are large;[11] there remain wide differences in views. An important consideration is that, once positive feedbacks begin, they may

[10] One line of evidence is that carbon dioxide levels have varied closely with the Earth's temperature in and out of glacial periods over the past million years. These cycles are mostly triggered by changes in the Earth's orbit, tilt, and wobble. In some of these cycles, temperatures rose in advance of rising atmospheric carbon dioxide concentrations. Scientists generally interpret this as a tendency for positive climate warming feedbacks that increase carbon dioxide concentrations which then enhance warming, etc.—that the net positive feedbacks *amplify* an initial climate warming.

[11] Positive feedbacks could increase if and when, for example, large tracts of forests die back as a response to exceeding their climate thresholds of tolerance, or current permafrost thaws and releases the carbon it contains, or if reservoirs of methane hydrates destabilize.

be essentially irreversible and, at least theoretically, lead to "runaway warming." A few of the major feedbacks are clouds, vegetation, snow and ice cover, and uptake or releases of GHG by soils and water bodies. Forests, for example, provide both negative and positive feedbacks. On the one hand, higher CO_2 concentrations in the atmosphere tend to fertilize their growth (if other conditions are not limiting) and forests may grow more rapidly with greater warmth and precipitation; these factors could dampen initiated warming. On the other hand, forests thrive within certain bounds of growing conditions; if their climate conditions change beyond those bounds, they are likely to grow more slowly and eventually die back, releasing the carbon they and forest soils store and enhancing the initiated climate change.

Internal Variability

The climate exhibits its own rhythms, or *internal variability*. The oscillation between El Niño and La Niña events is an example of internal climate variability that has important effects on economies and ecosystems in the Pacific basin (including across the United States). Another is the North Atlantic Oscillation. Internal variability may be difficult to distinguish from decadal-scale climate change. Such patterns of variability also may be influenced by climate change.

Projections of Future Human-Induced Climate Change

Most climate science experts project that if GHG emissions are not reduced far below current levels, the Earth's climate would warm further, above natural variations, to levels never experienced by human civilizations. If, and as, the climate moves further from its present state, it would reconfigure the patterns and events to which current human and ecological systems are adapted, and the risk of abrupt changes would dramatically increase.

Scenarios of future GHG concentrations under current policies range from 500 ppm carbon dioxide equivalents[12] (CO_2e) to over 1,000 ppm CO_2e by 2100. These are projected to raise the global average temperature by at least 1.5° Celsius (2.7° Fahrenheit) above 1990 levels,[13] not taking into account natural variability. The estimates considered most likely by many scientists are for GHG-induced temperature increases around 2.5 to 3.2° C (4.5 to 5.8° F) by 2100.[14] There is a small but not trivial likelihood that the GHG-induced temperature rise may exceed 6.4°C (11.5° F) above natural variability by 2100.[15]

[12] In order to show multiple gases of different potencies on a single scale, GHG have been indexed relative to the effect that a mass of CO_2 would have over several time periods (because GHG remain in the atmosphere for different lengths of time, from days to tens of thousands of years). The index used for these estimates uses a 100-year time horizon, the most frequently used period.

[13] Intergovernmental Panel on Climate Change Working Group I, *Climate Change 2007: The Physical Basis* (Cambridge, UK: Cambridge University Press, 2007).

[14] As a point of reference, the global mean annual temperature during the 20th century is estimated to have been approximately 13.9° Celsius (57.0° Fahrenheit), according to NOAA's National Climate Data Center.

[15] Ibid.

As context, the global average temperature at the Last Glacial Maximum has been estimated to be about 3 to 5° C (5.4 to 9° F) cooler than present,[16] and is estimated currently to be approaching the highest level experienced since the emergence of human civilizations about 8,000 years ago.[17]

Future climate change may advance relatively smoothly or sporadically, and some regions are likely to experience more fluctuations in temperature, precipitation, and frequency or intensity of extreme events than others. Almost all regions are expected to experience warming; some are projected to become warmer and wetter, while others would become warmer and drier. Sea levels could rise due to ocean warming alone on average between 7 and 23 inches by 2100. Adding to that estimate would be the effects of poorly understood but possible accelerated melting of the Greenland or Antarctic ice sheets. Recent scientific studies have projected a total global average sea level to rise in the 21st century, depending on GHG scenarios, ice dynamics, and other factors, in the range of 2 to 2.5 feet, with a few estimates ranging up to 6.5 feet.[18] Continued warming could lead to additional sea level rise over subsequent centuries of several to many meters. Improving understanding of ice dynamics is a high priority for scientific research to improve sea level rise projections.

Patterns consistent among different climate change models have led to some common expectations: GHG-induced climate change would include more heat waves and fewer extreme cold episodes; more precipitation on average but more droughts in some regions; and generally increased summer warming and dryness in the central portions of continents. Regional changes may vary from the global average changes, however. Scientists also expect precipitation to become more intense when it occurs, thereby increasing runoff and flooding risks.

Precipitation is a particularly challenging component of projecting future climate. For example, for the contiguous United States, recent climate modeling consistently anticipates overall temperature increases, but different models produce a wide range of precipitation changes, from net decreases to net increases.[19] This is particularly problematic in that precipitation, and its characteristics, is closely associated with impacts on agriculture, water supply, streamflows, and other critical systems.

Scientific expectations and model projections consistently point to a global average increase in precipitation with strong variations across regions and time. Generally, dry areas are expected to get dryer, and wet regions are expected to get wetter. In many regions, the increase in evapotranspiration is expected to exceed the increase in precipitation, resulting in general drying of soils and increasing risks of droughts. Precipitation, when it occurs, is expected to be more intense. There will be more energy available for storms, including hurricanes and thunderstorms, though whether they may increase in frequency remains unclear.

[16] Intergovernmental Panel on Climate Change Working Group I. *Climate Change 2007: The Physical Basis*. Cambridge, UK: Cambridge University Press, 2007. Executive Summary.

[17] Highest temperatures of the Holocene may have occurred in one or more periods some 5,000 to 8,000 years ago, although sufficient data are not available for all parts of the globe to have reliable estimates of average global temperature. The oldest cities discovered date from approximately the same period, such as the extensive settlement of Byblos in present-day Lebanon, by about 6,000 years ago, or Medinat Al-Fayoum in Egypt, about 6,000 years old. Since the early to mid-Holocene, however, average temperatures appear to have been declining slowly, with notable periods of warming and cooling. The changes entailed in Holocene climate variability have been significant in terms of effects on humans and ecosystems, and have led to both benefits to, and the demise of, numerous civilizations.

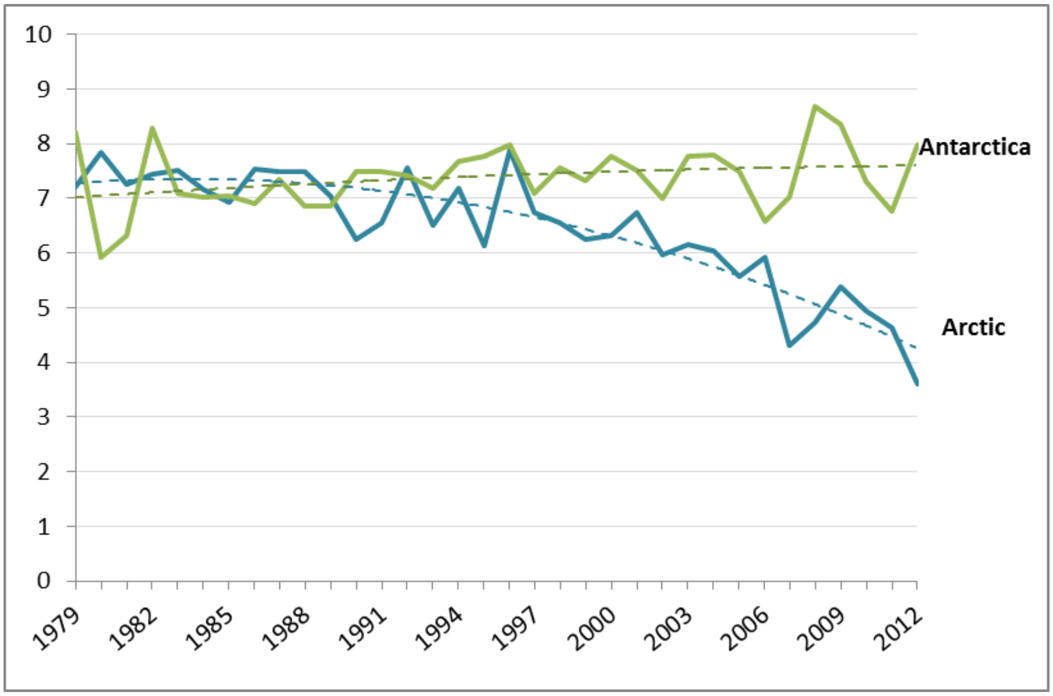
[18] See discussion in National Research Council. *Advancing the Science of Climate Change*. Washington DC, 2010, at p. 244.

[19] See, for example, climate change scenarios available from the U.S. Global Change Research Program at http://scenarios.globalchange.gov/sites/default/files/b/figures/UnitedStates/Ann_US_precip_a2.png, with notes at http://scenarios.globalchange.gov/node/1087. See also discussion in this report regarding dealing with uncertainties.

Sea ice cover in the Arctic is projected to continue its recent decline (**Figure 5**). Greenland is expected to continue ice loss, adding to sea level rise, with more uncertainty about what may happen to ice cover in Antarctica (**Figure 5**). Because Arctic sea ice already floats on water, its melting would not increase sea levels, but large scale melting of land-based ice in Greenland and Antarctica could increase average sea levels by as many as 2 meters by 2100 and several more meters over coming centuries.

Figure 5. Sea Ice Extent in Arctic (September) and Antarctica (April), 1979 to 2012

(in millions of square kilometers)



Source: CRS figure from data at the National Snow and Ice Data Center (extracted March 29, 2013), at http://nsidc.org/data/docs/noaa/g02135_seaice_index/#monthly_graphs_format.

Notes: The dotted lines show the best polynomial fit (2-order) to each time series, as estimated by Excel. For both series, the polynomical fit was slightly better than a linear fit. See the National Snow and Ice Data Center website, referenced above, for further description of the underlying data.

Impacts of Climate Change

Nearly every human and natural system could be affected by climate changes, directly or indirectly. The U.S. Global Change Research Program has produced several assessments of scientific understanding of impacts of climate change on the United States.[20]

Climate Changes Would Affect A Wide Set of Human Systems

Changes in patterns of temperature, precipitation, sea levels, storms, and heat waves (among other indicators of climate) would affect, among other systems:

[20] Karl, Thomas R., Mellillo, Jerry M., and Peterson, Thomas C. (eds.) *Global Change Impacts in the United States*. U.S. Global Change Research Program. 2009. Such periodic assessments are required by the Global Change Research Act of 1990 (P.L. 101-606). A new national assessment of impacts on the United States is due in late 2013.

- water resources and delivery;
- agricultural productivity;
- the frequency and intensity of extreme weather events;
- spread of infectious diseases; air and water pollution levels;
- reliability of transportation, energy, and coastal protection systems;
- commodity prices;
- insurance pay-outs; and
- migration of people and species.

There are many additional elements of the economy and society that could be affected by shifts in climate. Research on potential impacts of climate change is generally less funded and developed than on the climate system itself.

Whether climate changes are meaningful in a policy context arguably depends, on the one hand, on how they influence existing and emerging human systems, and on the other hand, the values people attach to different resources and risks. Past climate changes, often regional not global, contributed to major societal changes, including some large-scale migrations and even the demise of some civilizations.[21] Some climate changes likely stimulated technological advances, such as development of irrigation systems.

Many investments in current buildings, transportation, water systems, agricultural hybrid varieties, and other infrastructure were designed in the context of a climate of one or more decades ago, cooler on average than today. To the degree that climate patterns were factored into design, the investments typically presumed that climate would remain stable within historical bounds of variability. For example, levees may have been built to withstand a 100-year flood (1% chance to occur each year) according to historic runoff, streamflow, and storm surge conditions going back many decades. As climate changes produce greater, more intense precipitation and run-off, however, a 100-year flood may now be closer to the 50-year flood (2% chance flood), and potentially the 10-year flood within decades (10% change flood). If climate continues to change from the conditions for which infrastructure and practices were designed, the risks of losses due to maladaptation would increase.

A wide band of uncertainty surrounds projections of impacts of climate change and, in particular, the critical thresholds for non-linear or abrupt effects. Some impacts of climate change are expected to be beneficial in some locations with a few degrees of warming (e.g., increased agricultural productivity in some regions, less need for space heating, less cold weather mortality, opening of the Northwest Passage for shipping and resource exploitation). Most impacts are expected to be adverse (e.g., lower agricultural productivity in many regions, drought, rising sea

[21] There is a growing set of research on the relationship between past climate change and civilizations. A sample of recent research includes Buckley, B. M., K. J. Anchukaitis, D. Penny, R. Fletcher, E. R. Cook, M. Sano, L. C. Nam, A. Wichienkeeo, T. T. Minh, and T. M. Hong. "Climate as a Contributing Factor in the Demise of Angkor, Cambodia." *Proceedings of the National Academy of Sciences* 107, no. 15 (March 2010): 6748–6752; Cook, Edward R, Kevin J Anchukaitis, Brendan M Buckley, Rosanne D D'Arrigo, Gordon C Jacoby, and William E Wright. "Asian Monsoon Failure and Megadrought During the Last Millennium." *Science (New York, N.Y.)* 328, no. 5977 (April 23, 2010): 486–489; DeMenocal, PB. "Cultural Responses to Climate Change During the Late Holocene." *Science (Washington)* 292, no. 5517 (April 27, 2001): 667–673; Haug, G. H, D. Gunther, L. C Peterson, D. M Sigman, K. A Hughen, and B. Aeschlimann. "Climate and the Collapse of Maya Civilization." *Science* 299, no. 5613 (2003): 1731; Scholz, Christopher A., Thomas C. Johnson, Andrew S. Cohen, John W. King, John A. Peck, Jonathan T. Overpeck, Michael R. Talbot, et al. "East African Megadroughts Between 135 and 75 Thousand Years Ago and Bearing on Early-modern Human Origins." *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 42 (October 16, 2007): 16416–16421.

levels, spread of disease vectors, greater needs for cooling). Many impacts may be substantial but hard to assess as yet as "positive" or "negative," such as possible impacts on the structure of global financial markets. Risks of abrupt, surprising climate changes with accompanying dislocations are expected to increase as global average temperature increases; some could push natural and socioeconomic systems past key thresholds of tolerance.

Risks of future climate change would be reduced by efforts that reduce vulnerability and build resilience ("adaptation"). Some populations will have the resources to migrate and adapt successfully—even profit from new opportunities that will emerge—while others could lose livelihoods or lives. Adaptations can help mitigate impacts and damage costs, but also impose costs, often on those who can least afford them. Climate change will occur with different magnitudes and characteristics in different regions. The difficulties involved in improving predictions at regional and local scales will challenge preparations for climate change. To a large degree, climate change will expand the uncertainties that individuals and organizations face.

Climate change could have a wide array of effects on individuals, communities, and populations on a large scale. Many of these are expected to occur in small increments: shortages and increasing prices for clean water, rising food prices, higher rates of allergies and such illnesses as diarrhea or cholera, erosion of beaches, etc. At an increasing rate may be shocks, or distinct weather events, such as more extreme heat waves, severe droughts, or loss of industrial cooling systems when intake water is in short supply or is warmer than tolerable temperatures.[22]

Atmospheric Carbon Dioxide is Increasing Ocean Acidity

The **acidity of the surface waters of the oceans** has increased by about 26% over the past 150 years.[23] Ocean acidification has occurred along with the rise in atmospheric concentrations of CO_2. The oceans remove 25%-40% of the carbon dioxide emissions added annually to the atmosphere by burning fossil fuels. The carbon dioxide absorbed in the oceans decreases the water's pH, an indicator of increasing acidity. According to a National Research Council (NRC) report, the current rate of acidification "exceeds any known change in ocean chemistry for at least 800,000 years."[24] Research shows varying sensitivities of different marine species to rising acidity, making general statements about impacts of ocean acidification difficult. The NRC concluded,

> While the ultimate consequences are still unknown, there is a risk of ecosystem changes that threaten coral reefs, fisheries, protected species, and other natural resources of value to society. (*Executive Summary*, pp. 3-4)

Congress enacted the Federal Ocean Acidification Research and Monitoring Act of 2009 (P.L. 111-11, Section 12311, Subtitle D) to improve monitoring and research, to assess carbon storage in the oceans and potential effects on acidification and other ocean conditions, and to develop predictive models for future changes in ocean chemistry and marine ecosystems. The program is housed within the National Oceanic and Atmospheric Administration (NOAA), and coordinated with other agencies through an interagency plan through the National Ocean Council.

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[22] For examples of these risks to power plants, see Department of Energy (DOE), *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather*. July 2013. http://energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf. See also CRS Report R43199, *Energy-Water Nexus: The Energy Sector's Water Use*, by Nicole T. Carter.

[23] NRC Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment; National Research Council. "Executive Summary." In *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Prepublication. Washington, D.C.: The National Academies Press, 2010; Jacobson, Mark Z. "Studying ocean acidification with conservative, stable numerical schemes for nonequilibrium air-ocean exchange and ocean equilibrium chemistry." *Journal of Geophysical Research* 110 (April 2, 2005): 17 PP.

[24] Ibid.

Extreme events, chronic economic losses, or improved opportunities elsewhere are expected to prompt migration of millions of people, largely within countries, but also across national borders. Extreme events, greater variability, and uncertainty are expected to increase stress and mental health challenges. Some experts project that climate changes could amplify instabilities in countries with weak governance and increase security risks.[25] This may have implications for international political stability and security.[26]

For some experts and stakeholders, likely ecological disruptions (and limitations on species' and habitats' abilities to adapt at the projected rate of climate change) are among the most compelling reasons that humans must act to reduce their interference with the climate system. Some believe humans will have the wherewithal to cope, but non-human systems may not. As the degree and distribution of climate changes continue, ranges of species are likely to change. Climate change is highly likely to create substantial changes in ecological systems and services[27] in some locations, and may lead to ecological surprises.[28] The disappearance of some types of regional ecosystems raises risks of extinctions of species, especially those with narrow geographic or climatic distributions, and where existing ecological communities disintegrate.[29] One set of researchers found "a close correspondence between regions with globally disappearing climates and previously identified biodiversity hotspots; for these regions, standard conservation solutions (e.g., assisted migration and networked reserves) may be insufficient to preserve biodiversity."[30]

Selected, Related CRS Reports

CRS Report R43185, *Ocean Acidification*, by Harold F. Upton and Peter Folger.

CRS Report R41153, *Changes in the Arctic: Background and Issues for Congress*, coordinated by Ronald O'Rourke.

CRS Report RL34580, *Drought in the United States: Causes and Issues for Congress*, by Peter Folger, Betsy A. Cody, and Nicole T. Carter.

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[25] An example of this is the adverse weather events in early 2011 that led to spikes in food prices and contributed to demonstrations in Tunisia and Egypt. These, in turn, led to regime change, although one cannot attribute these events to climate change, as opposed to weather variability, and the political implications might have been very different in regimes with better economic performance, less income disparity, fewer allegations of corruption, and greater social resilience. The point remains, nonetheless, that societies are sensitive to climatic variables in many ways.

[26] Regarding risks to national security, see, for example, Defense Science Board Task Force on *Trends and Implications of Climate Change for National and International Security*. October 2011. http://www.acq.osd.mil/dsb/reports/ADA552760.pdf; and U.S. Department of Defense. Quadrennial Defense Review, February 2010. (pp. xv, 84-88) http://www.defense.gov/qdr/qdr%20as%20of%2029jan10%201600.pdf.

[27] Economists and scientists sometimes refer to "ecosystem services," which are the services that natural systems provide and for which, very frequently, humans do not typically pay. Ecosystems services include water filtration, filtering of air pollution, recreational and spiritual opportunities, etc. Even without being valued in capital markets, ecosystem services may be critically important to economies. For example, in many coastal areas, mangroves or wetlands provide valuable buffering against frequent storm and flood events. If such ecosystem services did not exist, communities would have to pay for manufactured alternatives (e.g., sea walls) or risk incurring damages.

[28] For example, the very rapid spread of pine beetles in recent years was unexpected and caused large damages (although a temporarily inexpensive supply of timber) in a very short period. See CRS Report R40203, *Mountain Pine Beetles and Forest Destruction: Effects, Responses, and Relationship to Climate Change*.

[29] Malcolm, Jay R., Canran Liu, Ronald P. Neilson, Lara Hansen, and Lee Hannah. "Global Warming and Extinctions of Endemic Species from Biodiversity Hotspots." *Conservation Biology* 20, no. 2 (2006): 538-548.

[30] John W. Williams, Stephen T Jackson, and John E. Kutzbach, "Projected distributions of novel and disappearing climates by 2100 AD," *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 14 (April 3, 2007).

CRS Report R43199, *Energy-Water Nexus: The Energy Sector's Water Use*, by Nicole T. Carter.

CRS Report R42611, *Oil Sands and the Keystone XL Pipeline: Background and Selected Environmental Issues*, coordinated by Jonathan L. Ramseur.

CRS Report R42756, *Energy Policy: 113th Congress Issues*, by Carl E. Behrens.

CRS Report R42613, *Climate Change and Existing Law: A Survey of Legal Issues Past, Present, and Future*, by Robert Meltz.

CRS Report R43120, *President Obama's Climate Action Plan*, coordinated by Jane A. Leggett.

CRS Report R42756, *Energy Policy: 113th Congress Issues*, by Carl E. Behrens.

CRS Report RL34266, *Climate Change: Science Highlights*, by Jane A. Leggett.

CRS Report R41973, *Climate Change: Conceptual Approaches and Policy Tools*, by Jane A. Leggett.

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